An Autonomous Above-Water System for the Validation of Ocean Color Radiance Data

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***Abstract*—An operational system for autonomous above-water radiance measurements, called the SeaWiFS Photometer Revision for Incident Surface Measurements (SeaPRISM), was deployed at the *Acqua Alta* Oceanographic Tower in the northern Adriatic Sea and used for the validation of remote sensing radiometric products in coastal waters. The SeaPRISM data were compared with simultaneous data collected from an independent in-water system for a wide variety of sun elevations along with different atmospheric, seawater, and sea state conditions. The average absolute differences between the above- and in-water determinations of water-leaving radiances (computed linearly) were less than 4.5% in the 412–555-nm spectral interval. A similar comparison for normalized water-leaving radiances showed average absolute differences less than 5.1%. The comparison between normalized water-leaving radiances computed from remote sensing and SeaPRISM matchup data, showed absolute spectral average (linear) differences of 17.0%, 22.1%, and 20.8% for SeaWiFS, MODIS, and MERIS, respectively. The results, in keeping with those produced by independent in-water systems, suggest the feasibility of operational coastal networks of autonomous above-water radiometers deployed on fixed platforms (towers, lighthouses, navigation aids, etc.) to support ocean color validation activities.**

***Index Terms*—Above-water radiometry, calibration and validation, ocean color, water-leaving radiance.**

I. Introduction

THE COASTAL Zone Color Scanner (CZCS) mission demonstrated the possibility of mapping the phytoplankton pigment concentration in the upper ocean layers with an optical remote sensor [1] and provided a worldwide picture of oceanic biomass [2], albeit only after compositing many years of data.

This achievement led to the development of a number of increasingly advanced ocean color sensors capable of producing global images for worldwide oceanographic studies and applications every two to three days. Among these are the Ocean Color and Temperature Scanner (OCTS), the Polarization and Directionality of the Earth's Reflectance (POLDER) sensor, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), the Moderate Resolution Imaging Spectroradiometer (MODIS), the Medium Resolution Imaging Spectrometer (MERIS), and the Global Imager (GLI). Although these satellite sensors have different specifications in terms of their spectral and spatial resolutions, a common element is the capability of detecting the water-leaving radiance $L_W(\lambda)$ at a variety of wavelengths, λ, i.e., the spectral radiance emerging from the sea and carrying information on the optically significant seawater constituents: phytoplankton, colored dissolved organic matter, and nonpigmented particulate matter.

The accurate determination of remote sensing $L_W(\lambda)$ values requires the absolute calibration of the space sensor and the removal of the atmospheric perturbing effects, i.e., the discrimination of $L_W(\lambda)$ from the total radiance $L(\lambda)$ measured by the spaceborne sensor viewing the sea through the atmosphere. The accuracy of the absolute calibration and the effectiveness of the atmospheric correction can be determined by comparing contemporaneous satellite derived and *in situ* $L_W(\lambda)$ data or, alternatively, derived quantities like the normalized water-leaving radiance $L_{WN}(\lambda)$ and remote sensing reflectance $R_{\mathrm{rs}}(\lambda)$. The generalized process of ground truth comparison under a wide range of environmental conditions is usually called validation. The more specific process of maintaining the agreement between the spaceborne sensor and sea truth observations is usually called vicarious calibration. Both activities are major tasks of ocean color missions and require highly accurate *in situ* data [3]. The compulsory *in situ* $L_W(\lambda)$ values can be produced using above- or in-water optical measurement methods.

The most common above-water methods for producing $L_W(\lambda)$ make use of measurements of the total radiance $L_T(\varphi, \theta, \lambda)$ taken while pointing a radiance sensor at the sea with relative azimuth φ with respect to the sun, and nadir viewing angle θ. The $L_T(\varphi, \theta, \lambda)$ values are then corrected for the sky radiance $L_i(\varphi, \theta', \lambda)$ reflected by the sea surface into the field of view of the sensor (the so-called sky glint). The $L_i(\varphi, \theta', \lambda)$ values are acquired in the same azimuthal plane as $L_T(\varphi, \theta, \lambda)$, but at a viewing angle $\theta' = \pi - \theta$ (i.e., equivalent to a θ zenith angle).

In-water methods make use of upwelling radiance profiles $L_u(z, \lambda)$ to extrapolate, as a function of water depth z, the subsurface radiance at null depth $L_u(0^-, \lambda)$, where the symbol 0^- denotes a depth immediately below the sea surface. The $L_u(0^-, \lambda)$ values are then transmitted through the sea surface to derive the (above-water) $L_W(\lambda)$ values.

The determination of $L_W(\lambda)$ from in-water methods relies on continuous or discrete $L_u(z, \lambda)$ profiles. Free-falling instruments or winched systems provide continuous in-water profiles and permit a comprehensive characterization of the water column, but their use is generally linked to research vessels. Although oceanographic cruises can provide data with a significant spatial extent, their temporal capabilities are restricted

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to relatively short time periods ranging from days to weeks. In-water moorings can supply almost continuous data collection, but their vertical resolution is quite poor (generally restricted to two to three discrete depths). In addition, their continuous operation makes the in-water sensors very susceptible to bio-fouling, and restricts their unattended use over long time periods (i.e., on the order of several weeks) to oligotrophic regions. In coastal areas, the accurate determination of $L_u(0^-, \lambda)$ from an $L_u(z, \lambda)$ profile requires high depth resolution to minimize wave effects in the extrapolation intervals, which are frequently reduced by gradients in the vertical distribution of optically significant constituents in the first few meters below the surface.

An autonomous above-water optical system will not be subjected to either in-water sampling problem, and is proposed here as a valid alternative to an in-water mooring and as a complement to regular oceanographic cruises for the production of a time series of $L_W(\lambda)$ data. The objectives of this study are to present the operational capabilities of the so-called SeaWiFS Photometer Revision for Incident Surface Measurements (SeaPRISM) instrument to support ocean color validation activities and to document its operational capabilities for water quality monitoring.

VI. Summary and Conclusion

The first operational SeaPRISM system was deployed at the AAOT in the northern Adriatic Sea from June 2002 to May 2003. The data collected within this time frame were compared with independent *in situ* data and with remote sensing data from different ocean color sensors. The comparison of SeaPRISM and WiSPER water-leaving radiances for various sun elevations along with different atmospheric, seawater, and sea state conditions, showed absolute spectral average (linear) differences within 4.5% in the 412–555-nm spectral interval. These differences were as high as 10.2% at 670 nm, and were primarily justified by the relatively high surface perturbation effects characterizing above-water optical data in the red part of the spectrum as well as diversity in the center wavelengths of the two instruments. Despite the observed differences, it is still relevant to consider the possibility of producing $L_W^{\mathrm{SP}}(\lambda)$ data in the red domain where their availability supports accuracy analyses of atmospheric corrections over coastal waters. The overall comparison of SeaPRISM and WiSPER data for both water-leaving radiances and normalized water-leaving radiances confirms the capability of the autonomous above-water system to produce data with an accuracy comparable to that of in-water systems and, consequently, to support ocean color validation activities.

The comparison results between normalized water-leaving radiances computed from remote sensing and SeaPRISM data, for the AAOT site, show absolute spectral average (linear) differences of 17.0%, 22.1%, and 20.8%, for SeaWiFS, MODIS, and MERIS, respectively.

The overall results support the feasibility of an operational coastal network of above-water radiometers deployed on fixed platforms (towers, lighthouses, navigation aids, etc.) which could: 1) operate as references for the validation and comparison of primary remote sensing optical data (normalized water leaving radiance and additionally, aerosol optical thickness) from different spaceborne sensors; 2) support vicarious calibration exercises when the characteristics of the site (spatial variability, adjacency effects, and bottom perturbations) allow for extrapolation of single-point *in situ* measurements to the satellite spatial resolution; 3) produce marine and atmospheric optical data for the creation of sites climatology; and 4) contribute to the monitoring of coastal water quality indexes (e.g., through spectral ratios much less affected by environmental and systematic uncertainties than the primary quantities) in challenging areas for remote sensing systems or in water moorings.

An extensive use of SeaPRISM systems in supporting ocean color and coastal monitoring activities would also suggest a further specialization of the basic CE-318 system through: 1) the adoption of center wavelengths only specific for ocean color applications and 2) the collection of a larger number of above-water measurement sequences and of sea and sky measurements. This further specialization could lead to the use of two systems in parallel, one for the atmosphere and the other for the marine applications.